

Spectral Network Based on Component Cells under the SOPHIA European Project

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Abstract. In the frame of the European project SOPHIA, a spectral network based on component (also called isotypes) cells has been created. Among the members of this project, several spectral sensors based on component cells and collimating tubes, so-called spectroheliometers, were installed in the last years, allowing the collection of minute-resolution spectral data useful for CPV systems characterization across Europe. The use of spectroheliometers has been proved useful to establish the necessary spectral conditions to perform power rating of CPV modules and systems. If enough data in a given period of time is collected, ideally a year, it is possible to characterize spectrally the place where measurements are taken, in the same way that hours of annual irradiation can be estimated using a pyrheliometer.

INTRODUCTION

State of the art of Concentrating Photovoltaics (CPV) systems and modules are based on multijunction (MJ) solar cells. These devices are composed of several subcells connected in series (usually 3 junctions). This feature limits the final photocurrent of the device to the minimum of the three subcells. Since each subcell converts a different part of the solar spectrum, any variation of the incident solar spectrum impacts on the set of photocurrents and consequently the output power of a CPV system based on MJ cells.

At this point it is relevant to see how solar spectrum varies and the main factors that influence on it, therefore on CPV system's performance [1]. The main reason of spectral changes comes from the atmosphere. Sunlight passes through it and the most relevant atmospheric components (as aerosols, measured by the Aerosol Optical Depth (AOD) and vapor of water, characterized by the Precipitable Water (PW)) absorb and/or scatter the sunlight at different wavelengths. Another relevant factor is the optical path that sunlight passes until it reaches Earth defined by the solar zenith angle and usually characterized by the Air Mass (AM). The previous spectral factors (AM, AOD and PW, ordered by its influence on the solar spectrum) are actually dependant on a set of more descriptive variables as geographic/physical ones (e.g. latitude, altitude, dust, pollution, closeness to a mass of water...). The comparative study of the variations of the previous parameters with their spectral influence on MJ cell performance can provide an interesting frame to classify different locations with respect the spectral influence and even to forecast the spectral influence from these geographic variables.

SPECTRAL MATCHING RATIO (SMR)

A component (also known as isotype) cell is optically equivalent to a MJ solar cell in which only one of the subcells is electrically connected, so the photogenerated current corresponds to the connected subcell regardless of the spectral distribution of the incident light [2,3]. Component cells with collimating tubes for collecting direct normal irradiance (DNI) are instruments for spectral characterization known as isotypes spectral sensors or spectroheliometers. Although isotypes sensors can be potentially developed for any MJ technology, lattice matched GaInP/InGaAs/Ge component cells are currently widely used as reference sensors to determine spectral conditions in CPV characterization.

From the photocurrents of a set of component cells we can define the so called Equivalent Irradiance for each subcell [4], as the normalized current to the reference spectrum and irradiance:

$$B_{subcell_i} = \frac{I_{L,subcell_i}}{I_{L,subcell_i,ref}} B_{ref} \quad (1)$$

Spectral Matching Ratio (SMR) is a spectral index that allows quantifying solar spectra. It is related to the variation of the current ratio of two subcell photocurrents at a given spectrum with respect the reference one. Since equivalent irradiances are calibrated at spectral and irradiance reference conditions, SMR can be easily formulated as:

$$SMR_{subcell_j}^{subcell_i} = \frac{B_{subcell_i}}{B_{subcell_j}} \quad (2)$$

When we are considering three junctions, there are three possible SMR, namely: top-middle, middle-bottom and top-bottom, so one of them is redundant. Since AM and AOD are mainly affecting the initial part of the spectrum and PW is clearly related to water peak absorptions that affect mostly middle-bottom wavelengths, SMR_{mid}^{top} and SMR_{bot}^{mid} are preferred. In this way, atmospheric parameters effects can be decoupled and easily correlated to a SMR variable.

SMR are gaining prominence in the CPV technology to fix prevailing spectral conditions by filtering, using as reference condition $SMR=1$ [5-9]. IEC62670-3 draft is currently including this approach.

SPECTRAL DESCRIPTION OF A LOCATION

Spectral Matching Ratios can be used beyond instantaneous filtering to determine prevailing spectral conditions, for instance, to describe spectrally the DNI energy that is received at a specific location. Annual periods are convenient due to the periodicity of solar energy, and in the same way the number of hours of annual irradiation is a representative number for a location, spectral characteristics are expected to be repeatable. These spectral patterns can be estimated with a spectroheliometer in the same way as annual irradiation is measured using a pyrheliometer.

Direct Normal Irradiation vs. Spectral Matching Ratios in Madrid

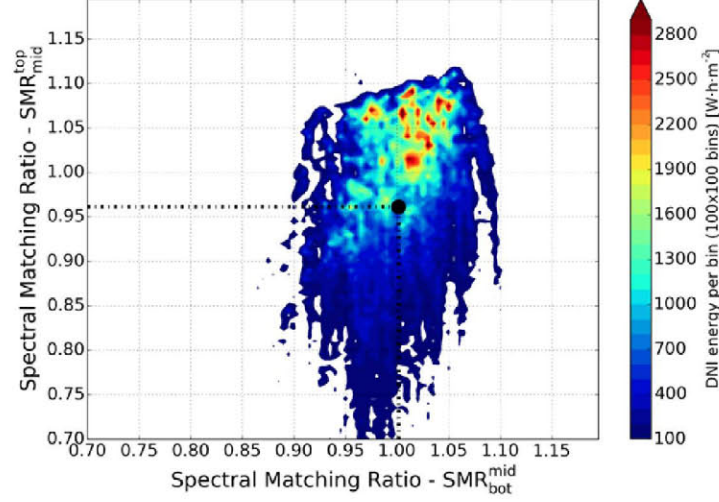


FIGURE 1. Spectral diagram of Madrid for the year 2013. It describes how the DNI energy is distributed according to spectral coordinates (SMRs)

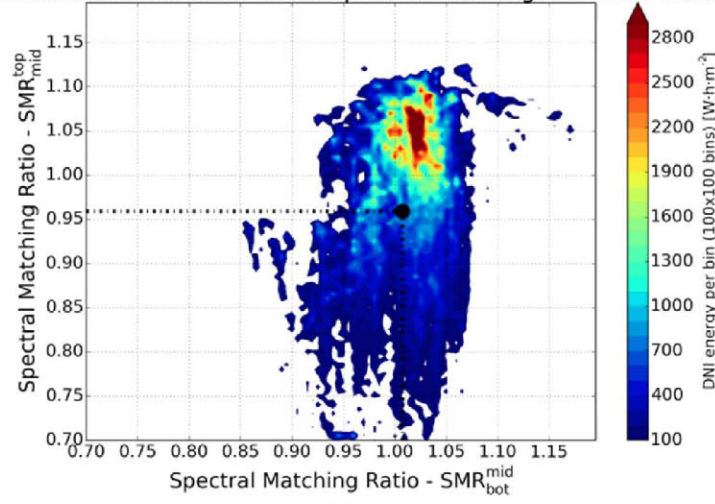
The spectral diagram of Fig. 1 shows how the DNI energy is distributed in the space of SMR coordinates [10] in Madrid. Both DNI and SMR's have been measured with high time resolution (one minute) during the whole year 2013. The graph shows that the energy is well limited in a spectral range of SMR_{mid}^{top} and SMR_{bot}^{mid} . The black dot indicates the SMRs barycenter, that is, the weighted average of the direct normal irradiation in spectral coordinates ($\overline{SMR}_{mid}^{top}$ and $\overline{SMR}_{bot}^{mid}$) which are respectively 0.96 and 1.00. Therefore, these parameters indicates where the DNI is located in terms of spectrum for a given location. The detailed formulation of this variable is:

$$\overline{SMR}_{subcell_j} = \frac{\int_{year} SMR_{subcell_i} \cdot E_{DNI} dt}{\int_{year} E_{DNI} dt} \quad (3)$$

Annual Reproducibility

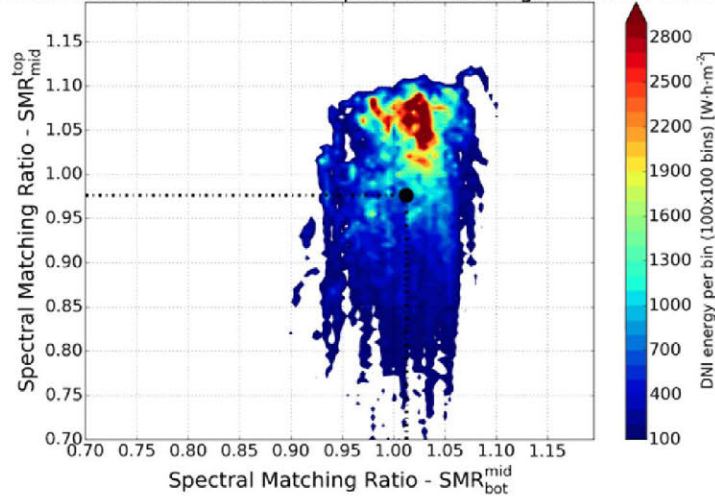
Years 2012 and 2014 have been also analyzed for the case of Madrid, and the spectral graphs have similar shape as can be seen in Fig. 2. The annual SMR and the dispersion among years (2012, 2013 and 2014) is $\overline{SMR}_{mid}^{top} = 0.96 \pm 0.8\%$ and $\overline{SMR}_{bot}^{mid} = 1.01 \pm 0.5\%$.

Direct Normal Irradiation versus Spectral Matching Ratios in Madrid



(a)

Direct Normal Irradiation versus Spectral Matching Ratios in Madrid



(b)

FIGURE 2. Spectral diagrams of Madrid to show reproducibility for the year 2012 (a) and 2014 (b)

SOPHIA SPECTRAL NETWORK

Under the SOPHIA European project [11], several partners have been collecting spectral data using spectroheliometers for at least one year. In Fig. 3 we can see the location of the institutions that are involved: Madrid (IES-UPM), Bourget-du-Lac (CEA-INES), Freiburg (Fraunhofer ISE) and Portici (ENEA).

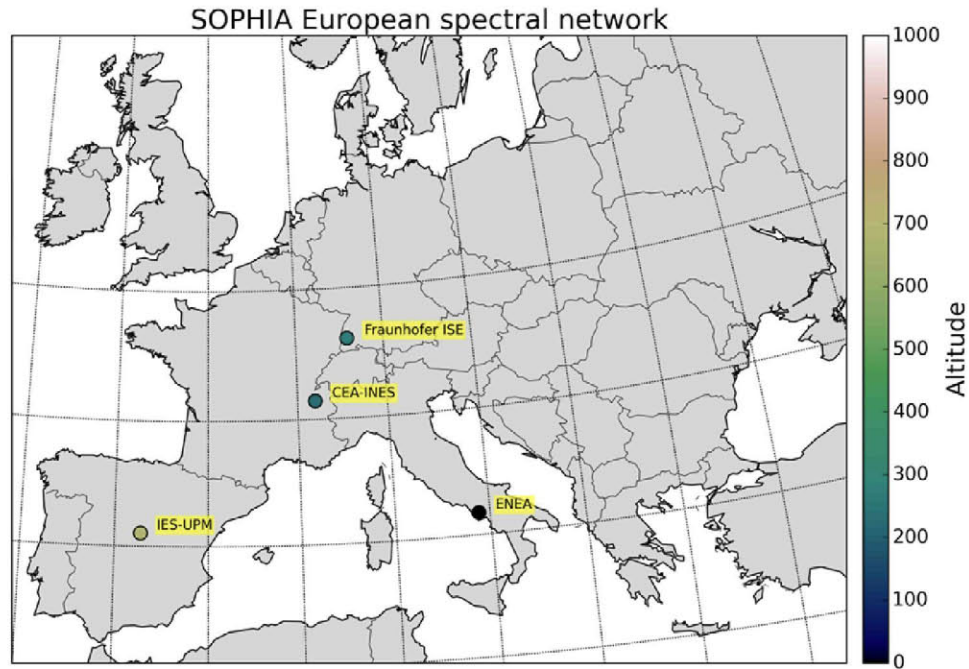
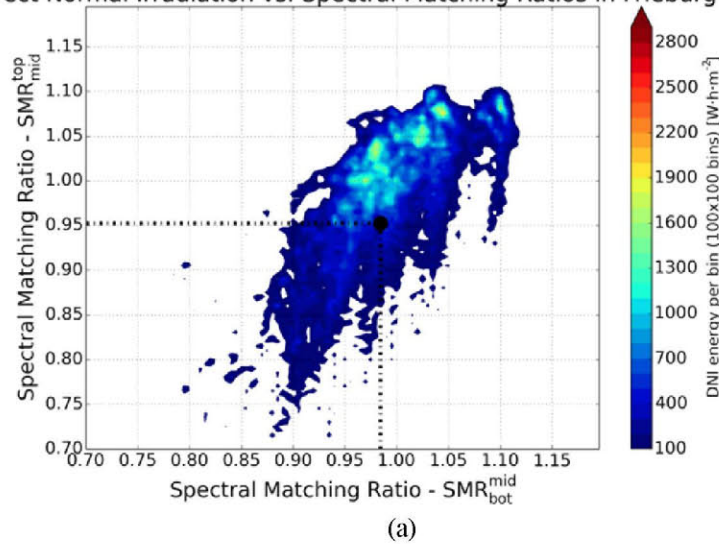


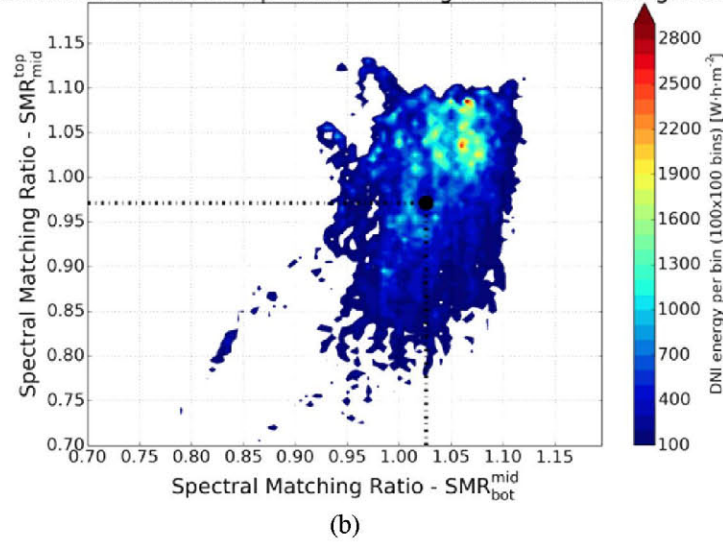
FIGURE 3. European map showing the institutions that are measuring using spectroheliometers composing the SOPHIA spectral network.

The corresponding spectral graphs can be seen in Fig. 4 and the shapes and sizes are already giving an idea that similar geographical conditions (especially latitude) are shaping in similar ways the spectral graphs.

Direct Normal Irradiation vs. Spectral Matching Ratios in Freiburg



Direct Normal Irradiation vs. Spectral Matching Ratios in Le Bourget-du-Lac



Direct Normal Irradiation vs. Spectral Matching Ratios in Portici

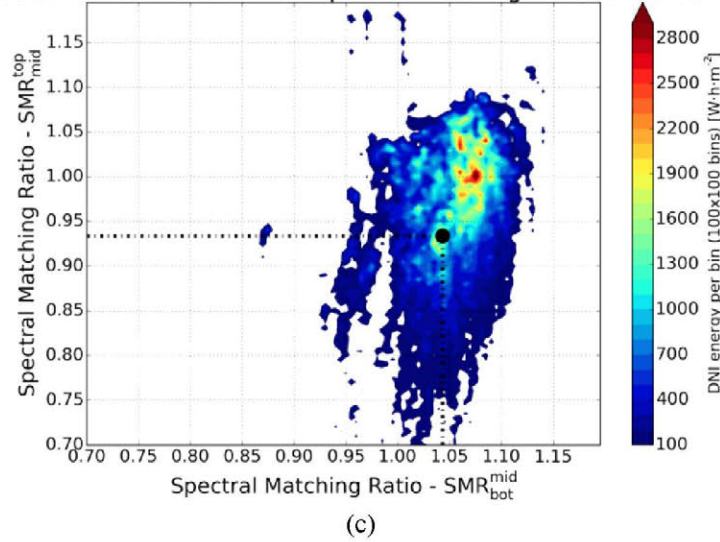


FIGURE 4. Spectral diagrams of Freiburg (a), Bourget-du-Lac (b) and Portici (c)

Geographical Analysis of Annual SMRs

In Fig. 5 the annual energy weighted SMR (\overline{SMRs}) of the different locations are plotted together. The first conclusion is that all the places are reddish from an annual energetic point of view, basically due to the low level of AOD used to define the ASTM G173 reference spectrum. We can quickly compare spectrally different locations plotting the annual SMR of each place. First let us remember the atmospheric factors that mainly influence on each SMR. SMR_{mid}^{top} is affected by AM and AOD, so the lower is AM (affected by latitude and altitude) and AOD (pollution, dust, soot ...), the higher is SMR_{mid}^{top} [12]. Similarly SMR_{bot}^{mid} is affected mainly by PW and AOD, so the closeness to mass of waters increases the SMR_{bot}^{mid} while it is reduced by AOD [12]. This can be seen in Fig. 5 in the analyzed locations. For example, we can compare Madrid and Portici, with similar latitudes and Mediterranean

climates. These similarities can be seen directly in the spectral graph of both places (see both spectral diagrams in Fig.1 and 3), quite comparable in shape and distribution of energy. However we see in Fig. 5 that Madrid presents higher values of $\overline{SMR}_{mid}^{top}$, due to its higher altitude (695 m vs. 0 m) and Portici has higher $\overline{SMR}_{bot}^{mid}$ due to be sited at sea level, presenting higher level of vapor of water in the atmosphere.

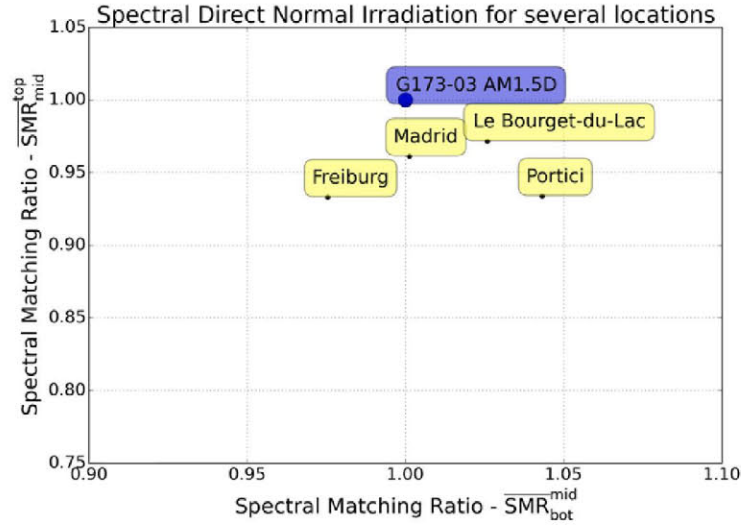


FIGURE 5. Annual SMRs (\overline{SMRs}) of the locations of the SOPHIA spectral network representing the how the DNI energy is shifted with respect the reference spectrum G173-03 AM1.5D

CONCLUSIONS

Obtaining the values of \overline{SMRs} of a site for a given technology indicates the kind of spectral influence and also gives an idea of the expected loss of energy due to spectral reasons; the higher is the deviation of \overline{SMR} from one (equivalent to reference spectrum), the larger is the loss due to spectral mismatch. Since not every place is potentially optimized to AM1.5D ASTM G173, a MJ solar cell could extract the maximum current if its subcells currents are matched to the local spectral conditions.

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This work made use of the Scipy stack [13], an open-source Python-based scientific computing environment.

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